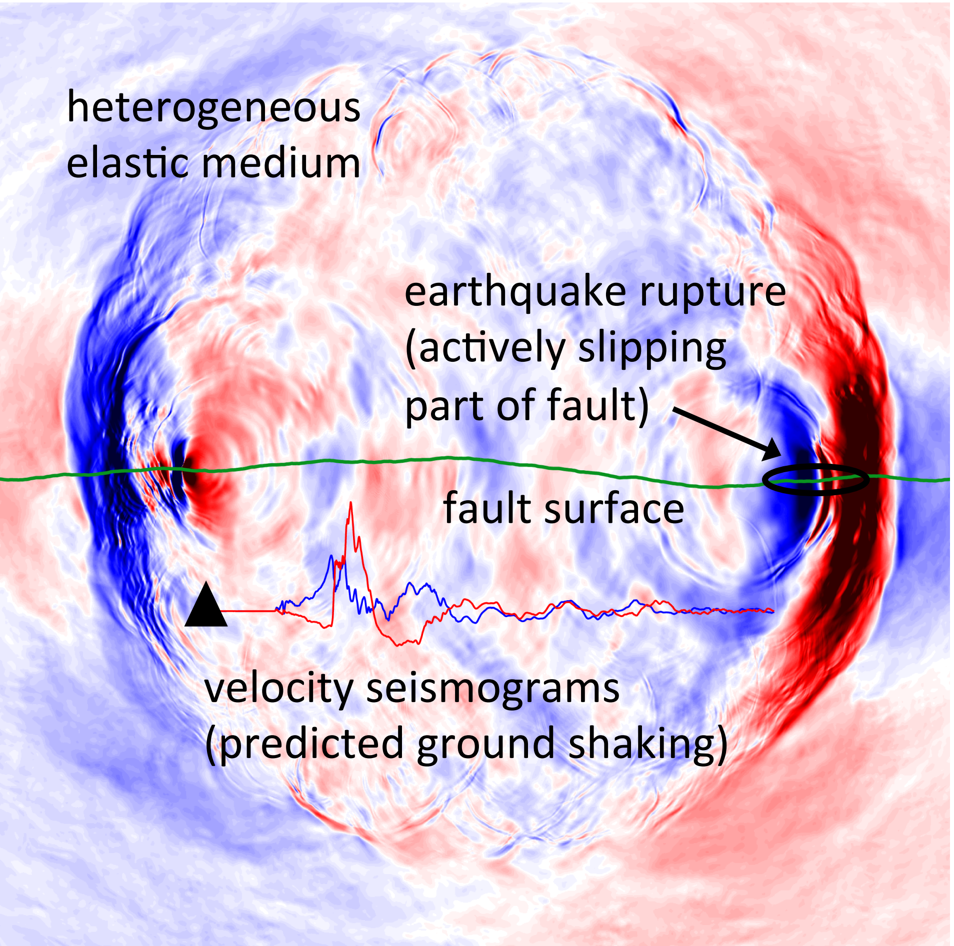
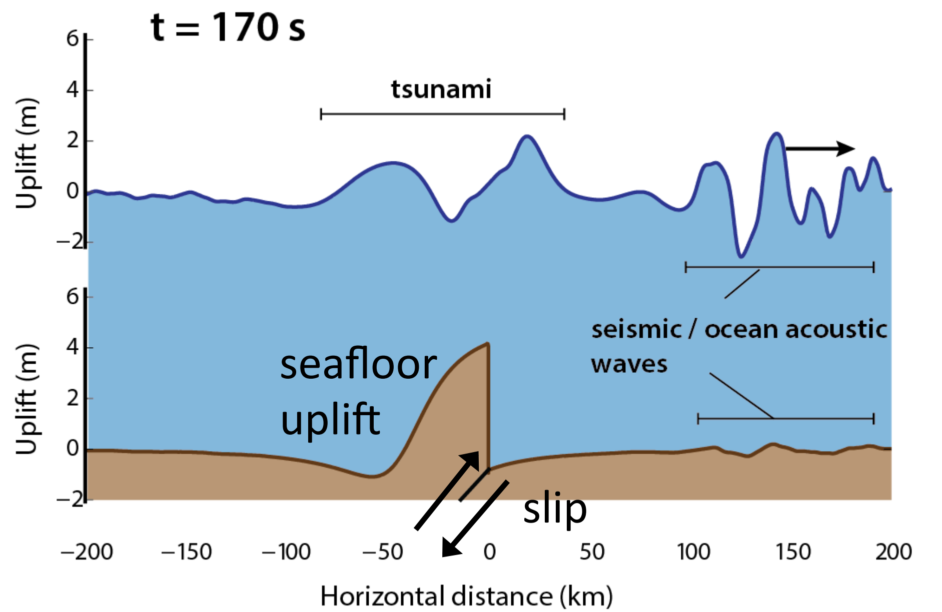
Improving Earthquake and Tsunami Hazard Assessment Using Geodynamics

Eric M. Dunham, Stanford Geophysics

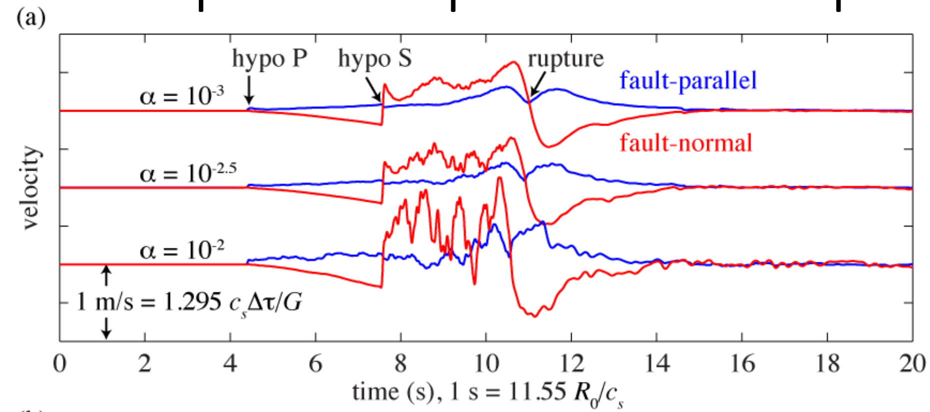
Ossian O'Reilly, Kim Torberntsson, Vidar Stiernström, Kali Allison, Gabe Lotto, Sam Bydlon, Jeremy Kozdon



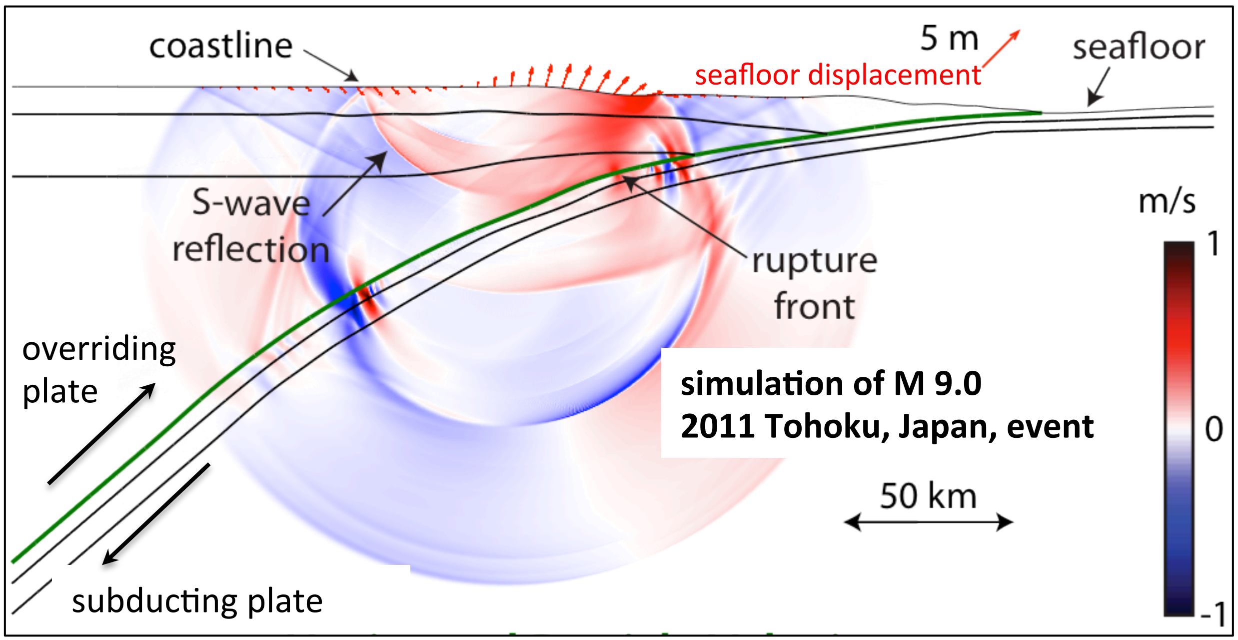


Earthquake rupture simulations provide practical outputs:

- strong ground motion, for seismic hazard assessment



- initial conditions for tsunami, for tsunami hazard assessment



…but these outputs are quite sensitive to model inputs, and in a highly nonlinear manner for dynamic source models!

Dynamic rupture simulations involve simultaneous solution of

- *elastic wave equation*
  (often with near-fault plasticity)
- *fault friction law*

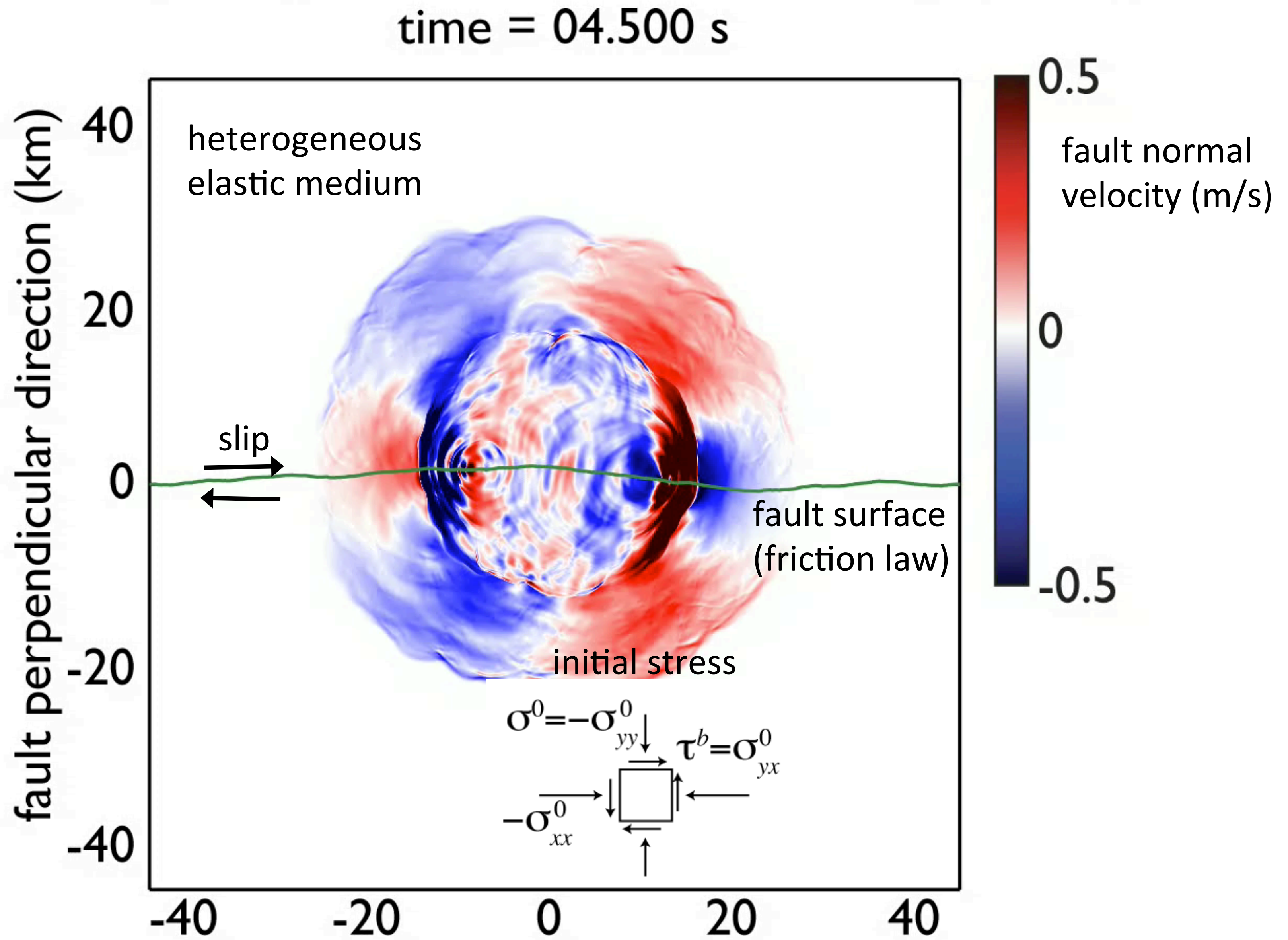
$$\tau = f(\sigma - p)$$

shear strength

friction coefficient (static vs. dynamic, slip-weakening, rate-and-state, etc.)

effective normal stress, influenced by poroelastic response

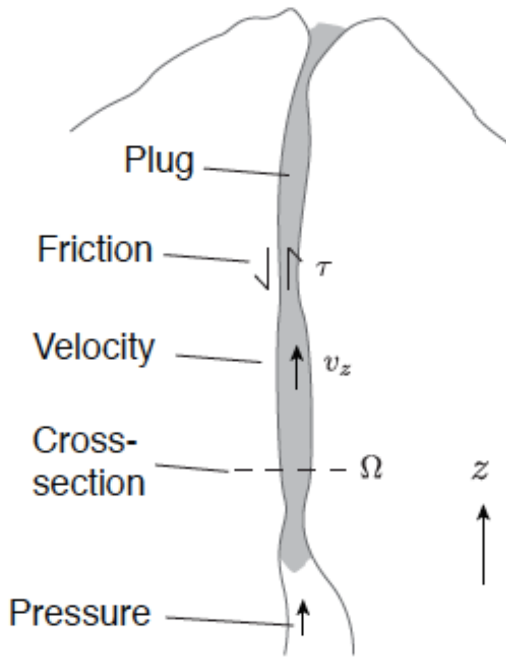
Dynamic Rupture Simulations: specify *initial stresses* and *friction law*, simultaneously solve for *rupture history* (slip) and *seismic wavefield*

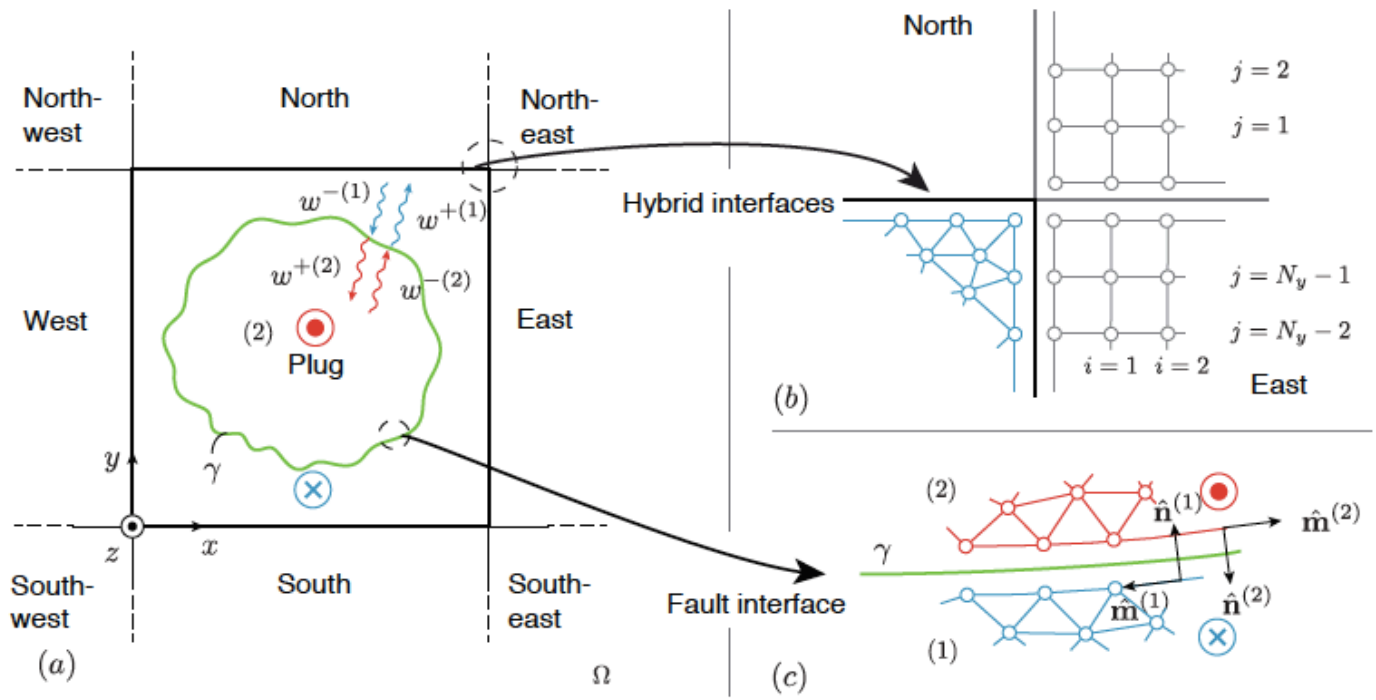


[Kozdon et al., 2013; Bydlon and Dunham, 2015]

Numerical Methods

We use a range of methods, mainly high-order finite differences on multiblock, curvilinear structured meshes, but occasionally finite volume on unstructured meshes or even AMR.



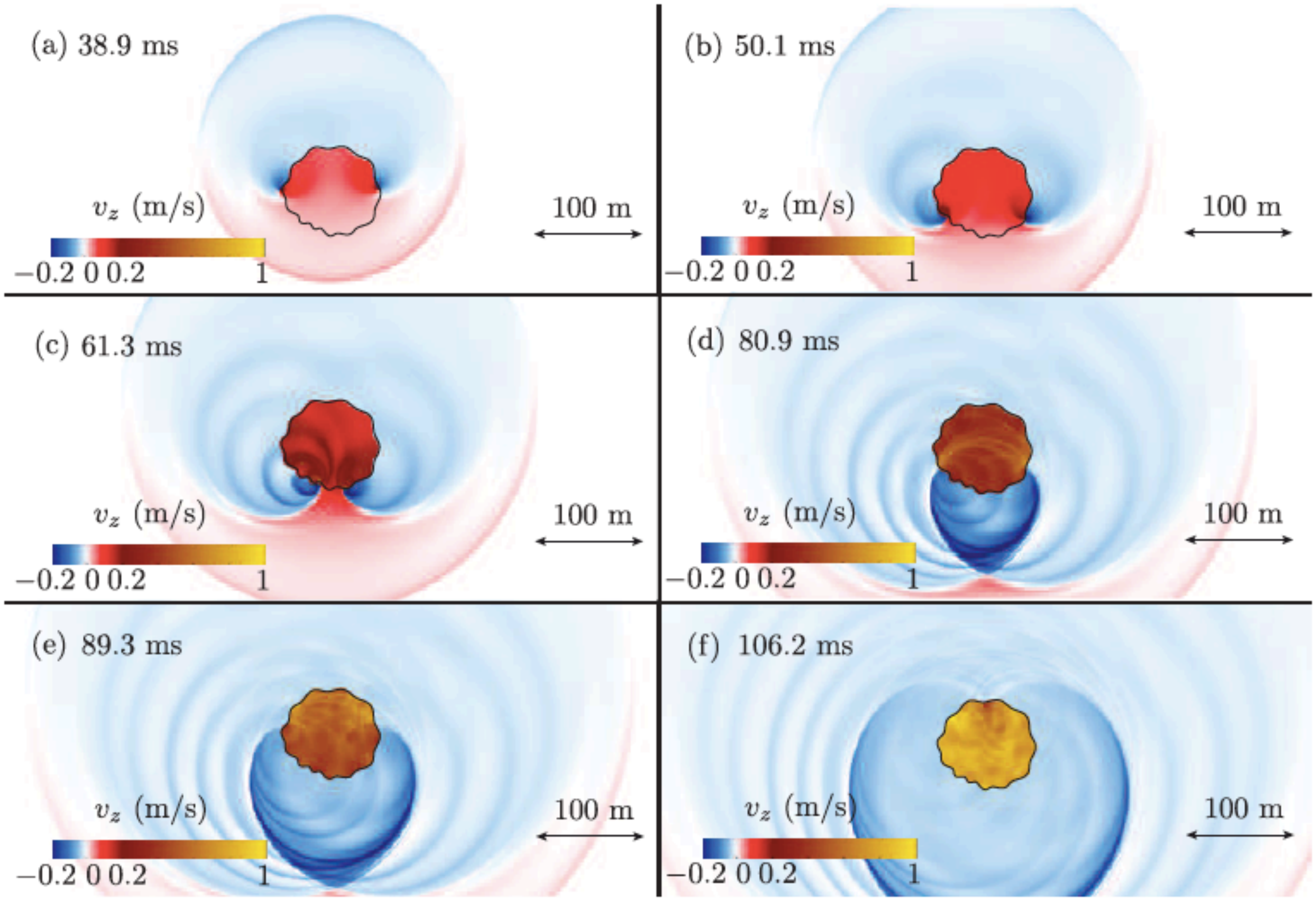


[O'Reilly, Nordstrom, and Dunham, 2015]

Key challenge is enforcing ***nonlinear fault interface conditions*** in stable and accurate manner. For single-event models, explicit time stepping with constant Δt.

Numerical Methods

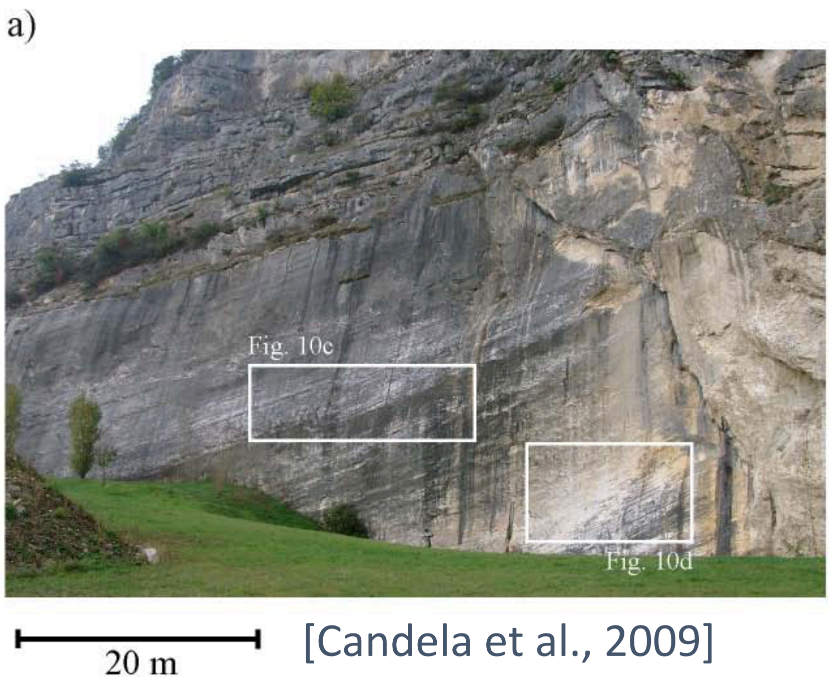
We use a range of methods, mainly high-order finite differences on multiblock, curvilinear structured meshes, but occasionally finite volume on unstructured meshes or even AMR.



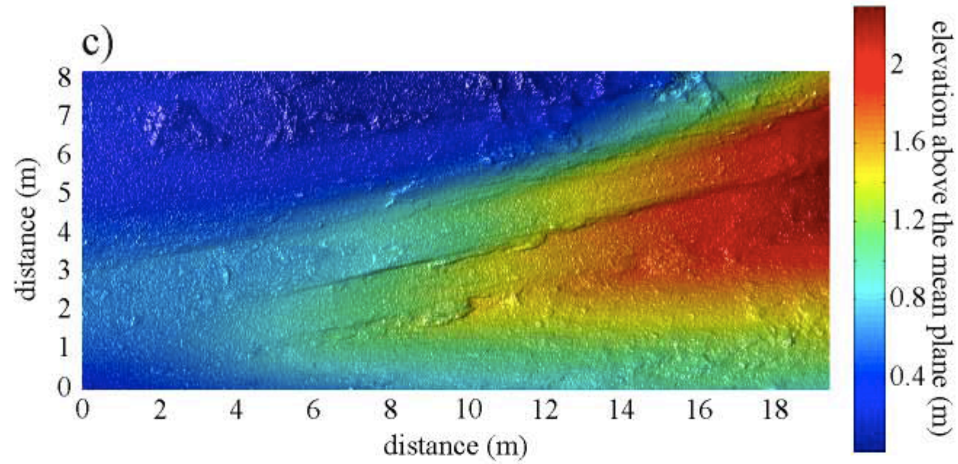
[O'Reilly, Nordstrom, and Dunham, 2015]

Key challenge is enforcing ***nonlinear fault interface conditions*** in stable and accurate manner. For single-event models, explicit time stepping with constant Δt.

Geometrical Complexity and Roughness of Faults

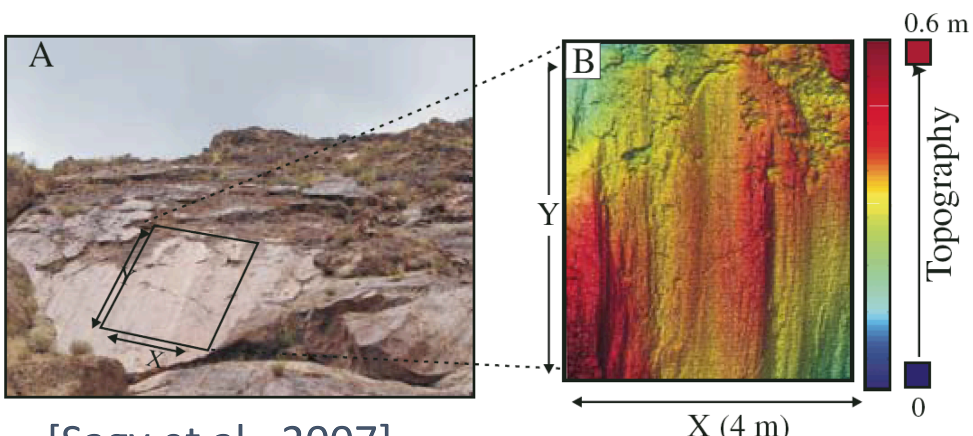


[Candela et al., 2009]



Roughness evident at all scales, faults are (self-similar) fractal surfaces

- geometric irregularities provide additional resistance to sliding
- waves excited at all wavelengths (λ~0.1-1 km → 1-10 Hz shaking)

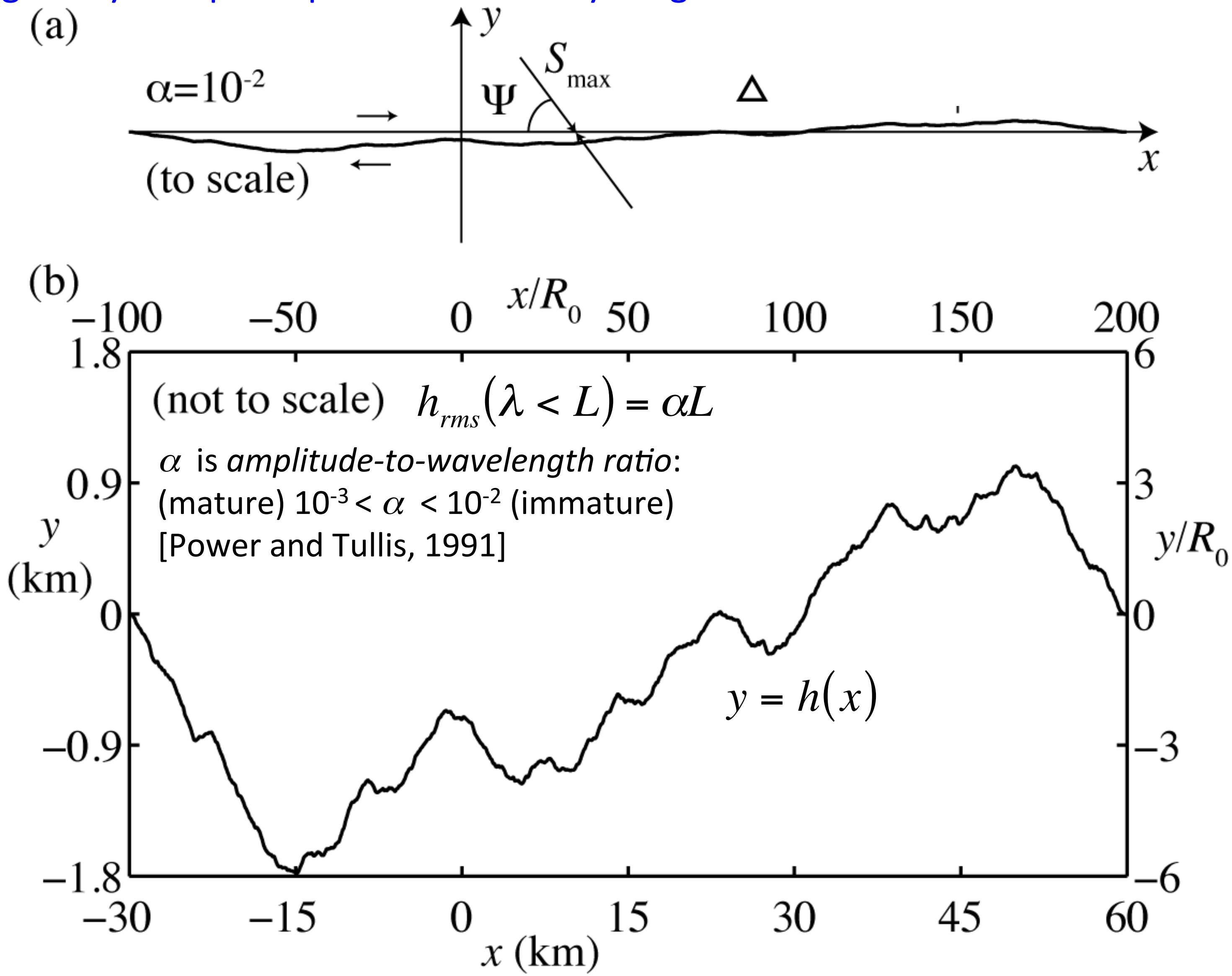


[Sagy et al., 2007]

Explore these issues using simulations of rupture propagation on rough faults

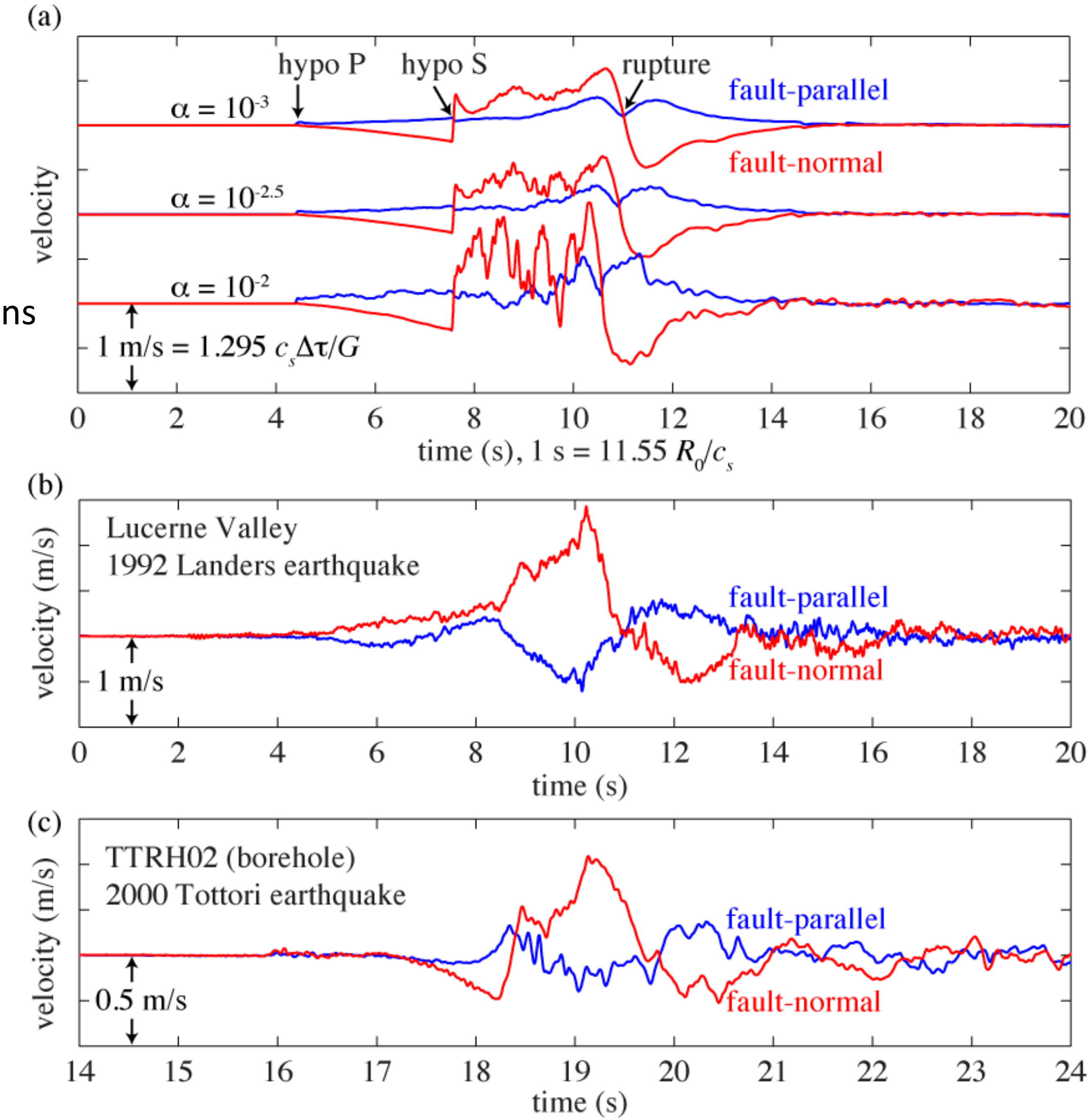
Self-Similar Fractal Profiles

dynamic rupture simulations on band-limited fractal fault ($\lambda>\lambda_{min}$)
and spatially uniform loading (and friction law parameters)
→ all irregularity in rupture process caused by roughness



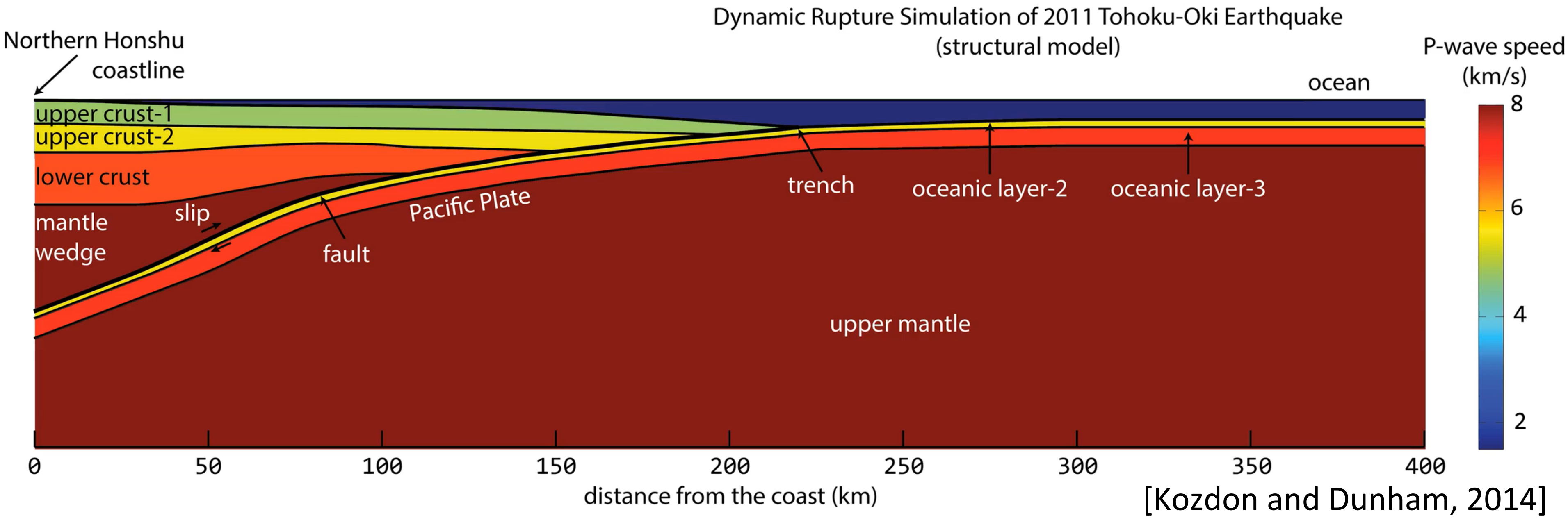
Velocity Seismograms

subsequent 3D simulations [e.g., Shi and Day, 2013; Duru and Dunham, 2016] have demonstrated consistency of these dynamic source models with ground motion observations (GMPEs)



[Dunham et al., 2011]

Megathrust Rupture Dynamics and Tsunami Generation



[Kozdon and Dunham, 2014]

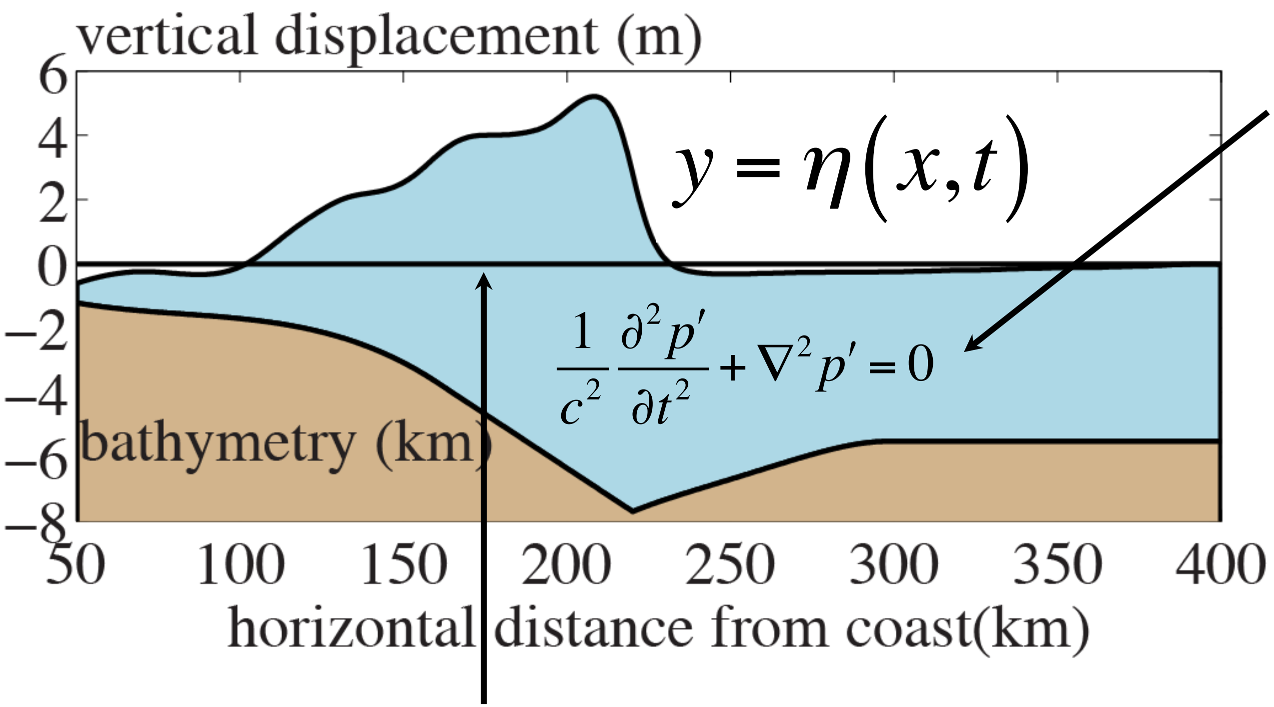
Motivating questions:

- how do frictional properties and elastic structure near trench and around frontal prism influence shallow slip and tsunami generation?
- what signals will be recorded by ocean bottom sensor networks?
- how can those signals be used to constrain rupture process and provide tsunami early warning?

Method: ***simulations accounting for all waves*** (seismic, acoustic, and tsunami), all self-consistently and with as few approximations as possible

Extending Earthquakes Simulations to Tsunamis

tsunamis (surface gravity waves) arise from ***gravity***: linearized governing equations must account for stratification in background hydrostatic state (we use Eulerian description)



1. in ocean, solve *acoustic wave equation* for pressure perturbation *p'* about initial hydrostatic state $p_0 = -\rho g y$ (same equation as in models without gravity; additional terms from stratification are negligible for Earth's gravity *g*)

$$
\begin{aligned}
0 &= p(y=\eta) \\
&= p(y=0) + \left.\frac{\partial p}{\partial y}\right|_{y=0} \eta + O\left(\eta^2\right) \\
&= p_0(y=0) + p'(y=0) \\
&\quad + \left(-\rho \left.\frac{\partial v_y}{\partial t}\right|_{y=0} - \rho g\right)\eta + O\left(\eta^2\right) \\
&= p'(0) - \rho g \eta + O\left(\eta^2\right)
\end{aligned}
$$

2. on *unperturbed* sea surface ($y=0$), enforce linearized free-surface boundary condition $p' - \rho g \eta = 0$, (rather than $p' = 0$) where $d\eta/dt = v_y$ (linearized kinematic condition)
→no need for time-dependent meshes

[Lotto and Dunham, 2015]

Compressible Ocean with Gravity

governing equations simplest in Eulerian description (fixed spatial coordinates)

$$\rho \frac{D\mathbf{v}}{Dt} + \nabla p = -\rho g \hat{\mathbf{y}} \qquad \text{(momentum balance)}$$

$$\frac{1}{\rho}\frac{D\rho}{Dt} + \nabla \cdot \mathbf{v} = 0 \qquad \text{(mass balance or continuity)}$$

$$\frac{1}{\rho}\frac{D\rho}{Dt} = \frac{1}{K}\frac{Dp}{Dt} \qquad \text{(equation of state, adiabatic)}$$

$$\frac{D}{Dt} = \frac{\partial}{\partial t} + \mathbf{v} \cdot \nabla \qquad \text{(material derivative)}$$

linearize for perturbations ($\rho = \rho_0 + \rho'$, etc.) about ocean at rest satisfying hydrostatic balance & eos:

$$\nabla p_0 = -\rho_0 g \hat{\mathbf{y}} \quad \text{and} \quad \rho_0 = \rho(p_0)$$

$$\rho_0 \frac{\partial \mathbf{v}}{\partial t} + \nabla p' = \boxed{-\rho' g \hat{\mathbf{y}}}$$

$$\frac{1}{K}\frac{\partial p'}{\partial t} + \nabla \cdot \mathbf{v} = \boxed{\frac{\rho_0 g \hat{\mathbf{y}}}{K} \cdot \mathbf{v}}$$

neglect these small terms

$$\Rightarrow \frac{1}{c^2}\frac{\partial^2 p'}{\partial t^2} + \nabla^2 p' = 0$$

acoustic wave equation (same as without gravity)

boundary condition on moving surface $y = \eta(x,t)$:

$$p = 0 \qquad \text{(traction-free surface)}$$

$$\frac{\partial \eta}{\partial t} + v_x \frac{\partial \eta}{\partial x} = v_y \qquad \text{(kinematic condition)}$$

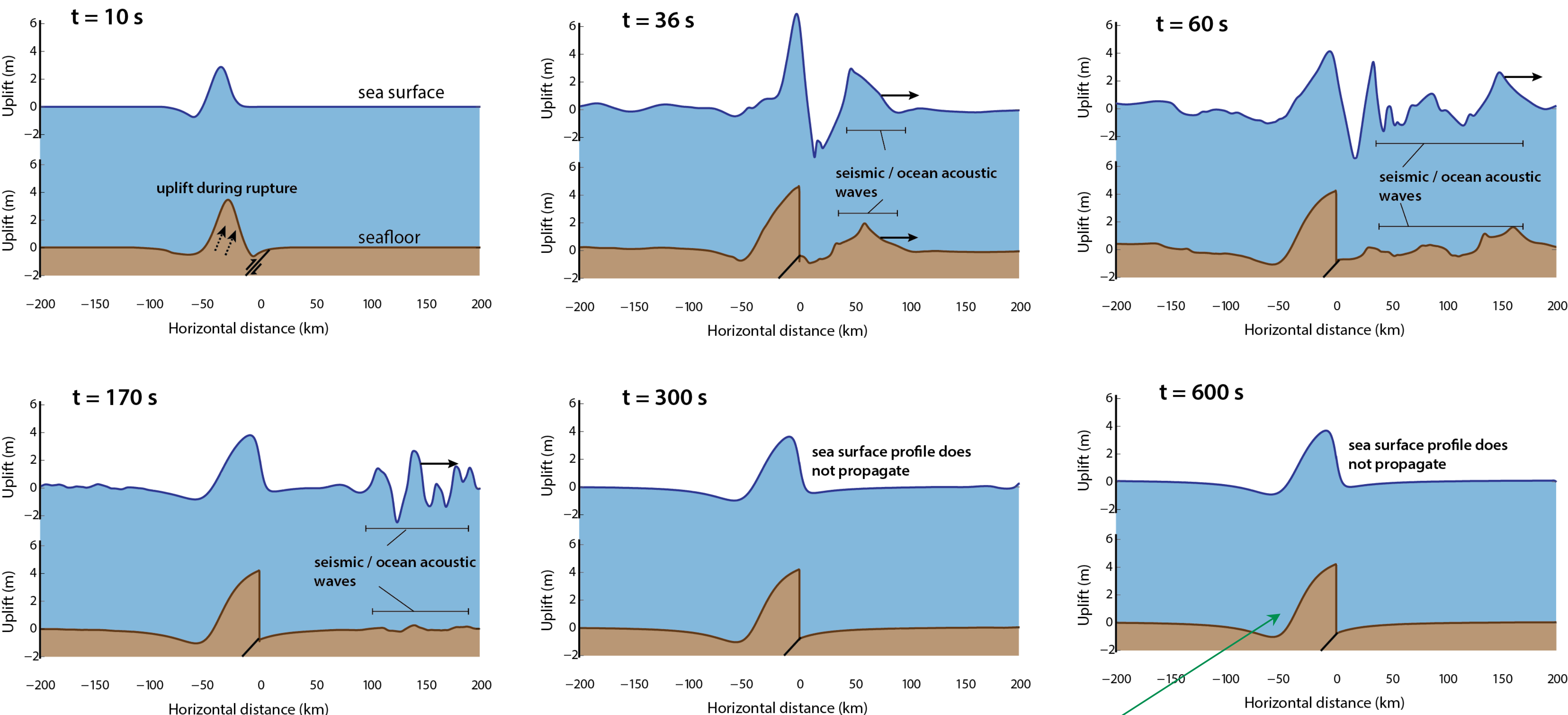
linearized conditions on initial surface $y = 0$:

$$p' - \rho_0 g \eta = 0 \quad \text{and} \quad \frac{\partial \eta}{\partial t} = v_y$$

[Lotto and Dunham, 2015]

Generation of Waves from Offshore Earthquakes

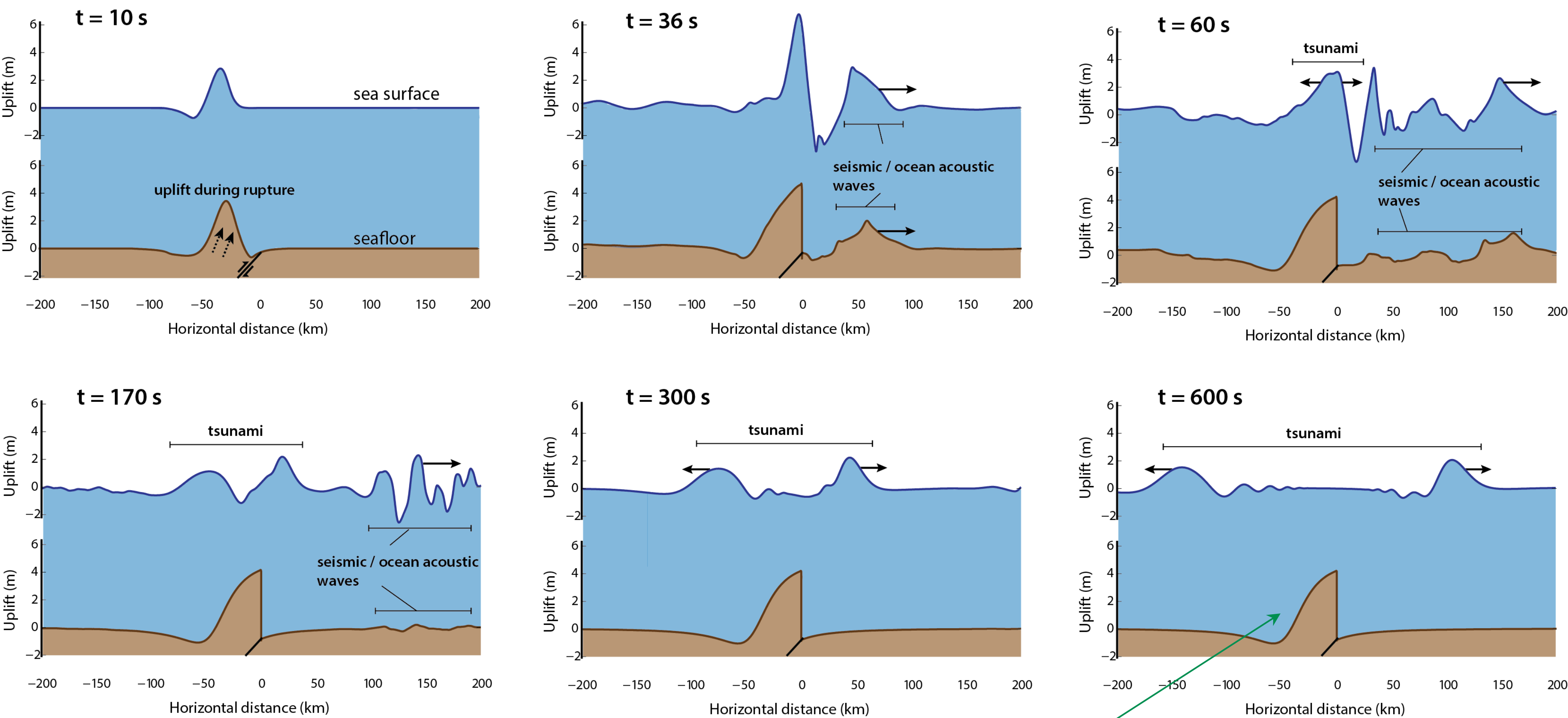
without gravity ($p'=0$ on top boundary)



matches static elasticity solution
for surface-breaking dislocation

Generation of Waves from Offshore Earthquakes

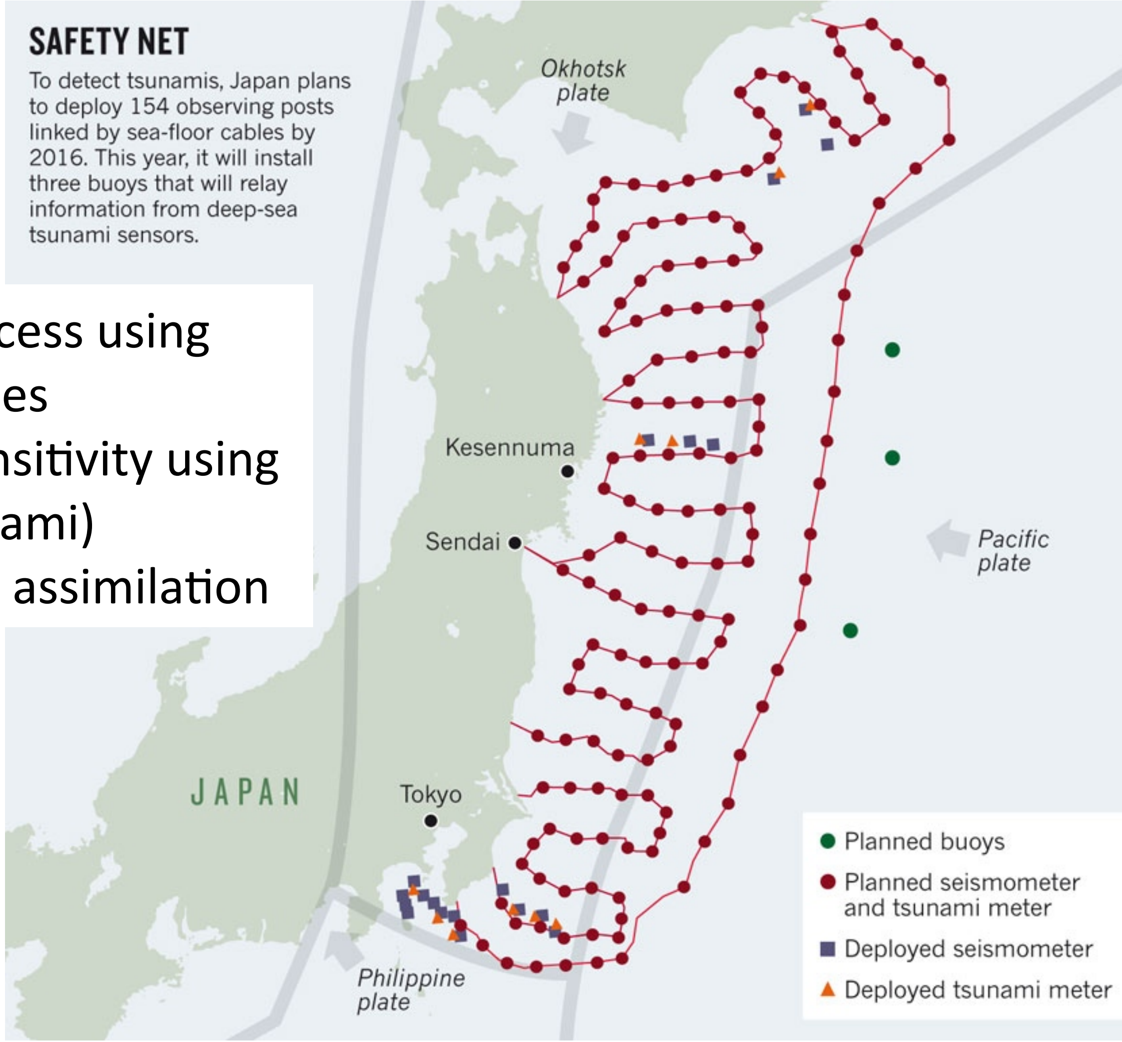
with gravity ($p' - \rho g \eta = 0$, $d\eta/dt = v_y$ on top boundary)



matches static elasticity solution
for surface-breaking dislocation

What will be measured with new offshore sensor networks?

- Resolve near-trench rupture process using OBS and high-rate pressure gauges
  → adjoint method for source sensitivity using all waves (seismic, acoustic, tsunami)
- Tsunami early warning with data assimilation



[Monastersky, 2012]

We Must Model Earthquake Sequences!

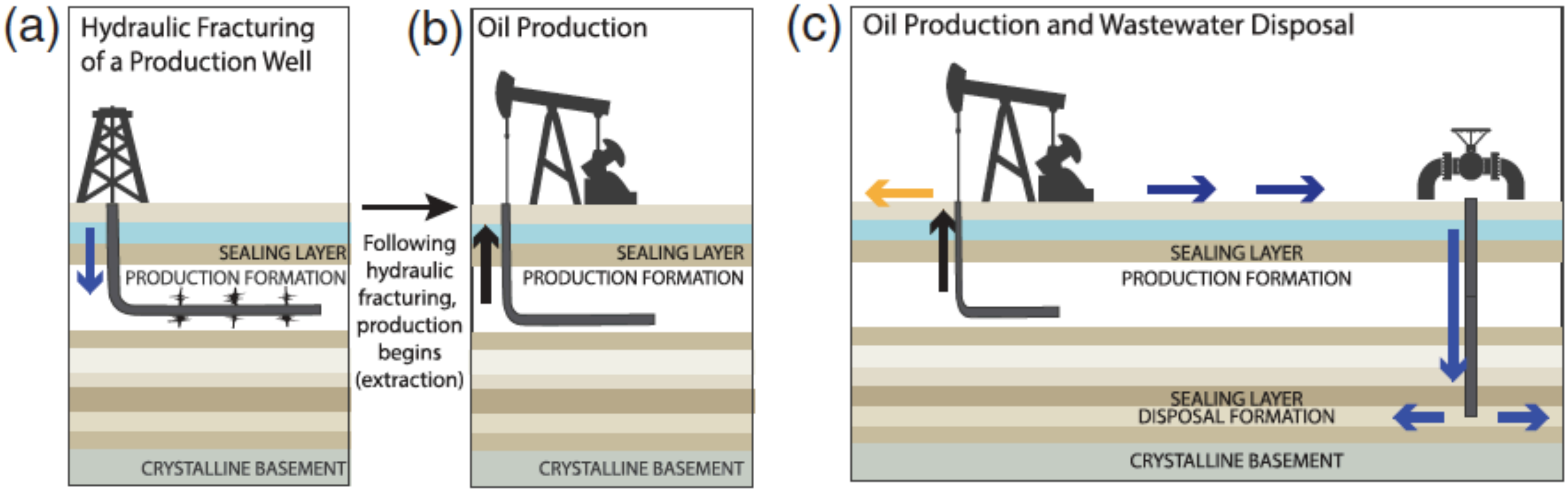
Rupture history is highly sensitive to initial stress:
- too low → arrest
- too high → unrealistically large slip and ground motion

Initial stress should be consistent with slip history and tectonic loading, poroelastic loading from fluid injection, viscous flow of lower crust and upper mantle, etc.!

→ Models must span interseismic period, postseismic response, and earthquake nucleation

Solve quasi-static (visco-/poro-) elasticity with rate-and-state friction → adaptive Runge-Kutta time stepping with error control

Poroelasticity and Induced Seismicity



[Rubinstein and Mahani, 2015]

how are pore pressure changes transmitted to faults in relatively impermeable basement? perhaps along permeable damage zones?

$$\boxed{\frac{\partial}{\partial x_j}\left[\left(K+\frac{G}{3}\right)\frac{\partial u_j}{\partial x_i}\right]+\frac{\partial}{\partial x_i}\left(G\frac{\partial u_i}{\partial x_j}\right)} = \frac{\partial(\alpha p)}{\partial x_i}$$

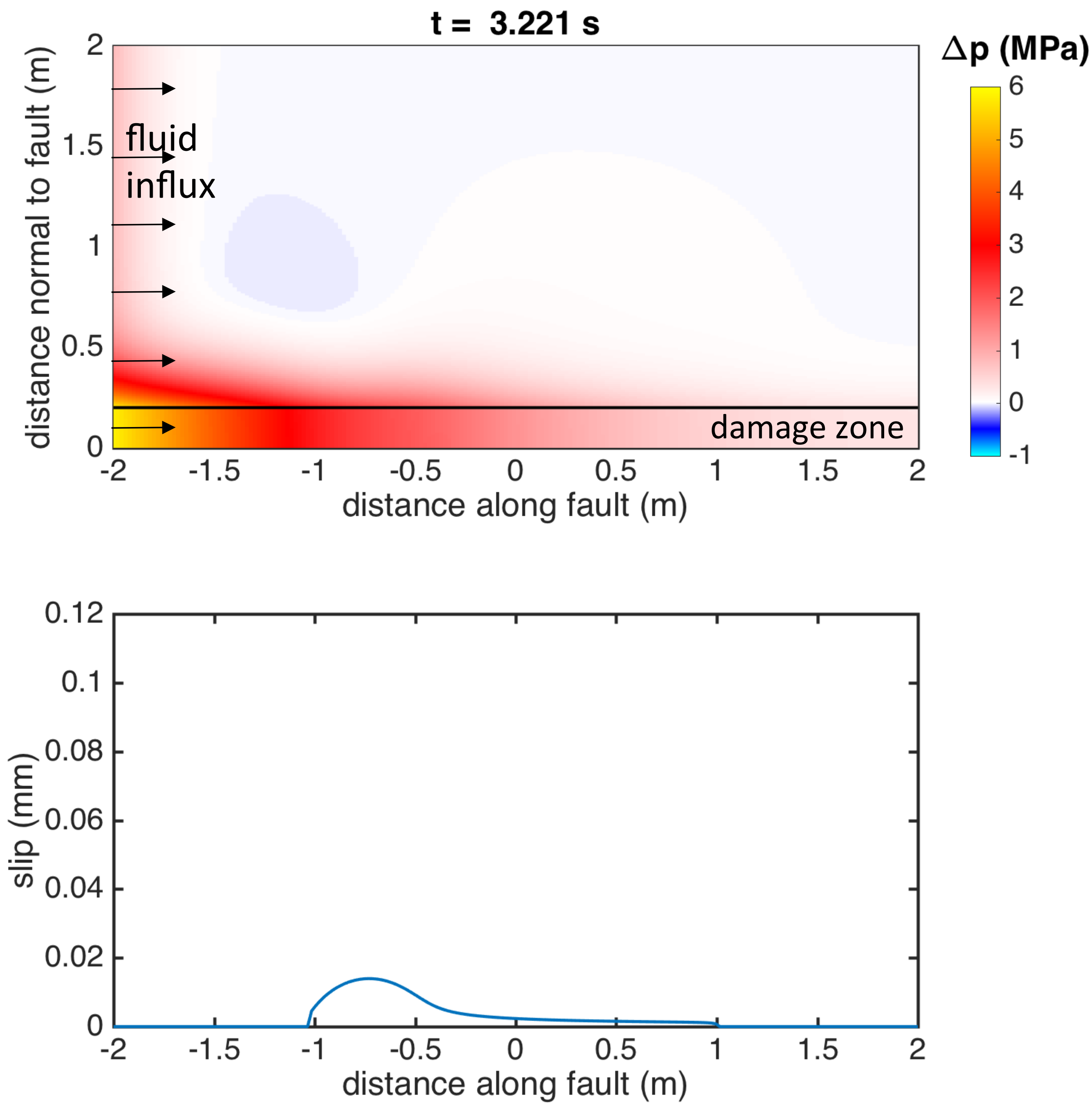
$$\boxed{\frac{1}{M}\frac{\partial p}{\partial t}-\frac{\partial}{\partial x_i}\left(\kappa\frac{\partial p}{\partial x_i}\right)} = -\alpha\frac{\partial \dot{u}_k}{\partial x_k}$$

mechanics

pore pressure diffusion

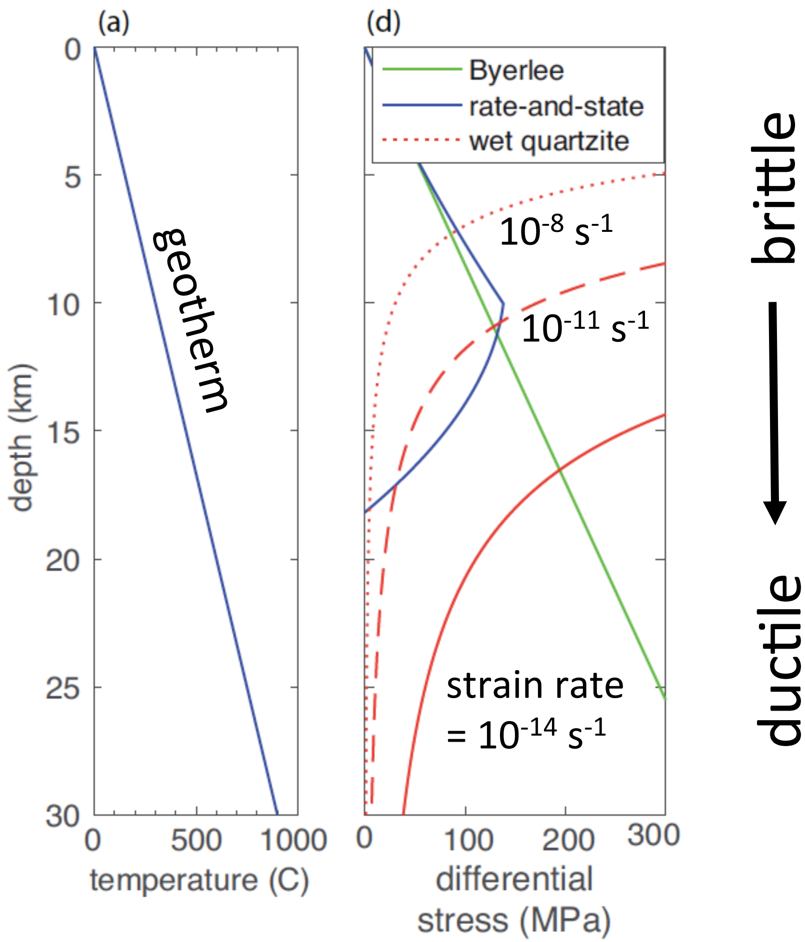
poroelastic coupling

Influx from left side along permeable damage zone, fault core impermeable



[Torberntsson, Stiernström, O'Reilly, Allison, and Dunham, work in progress, 2016]

Depth of Large Earthquakes:
Can they penetrate below brittle-ductile transition?



key question for hazard assessment because slip ∝ fault area

but various depth estimates (background seismicity, geodetic locking depth, etc.) can be quite different

→ turn to modeling with experimentally constrained friction and flow laws

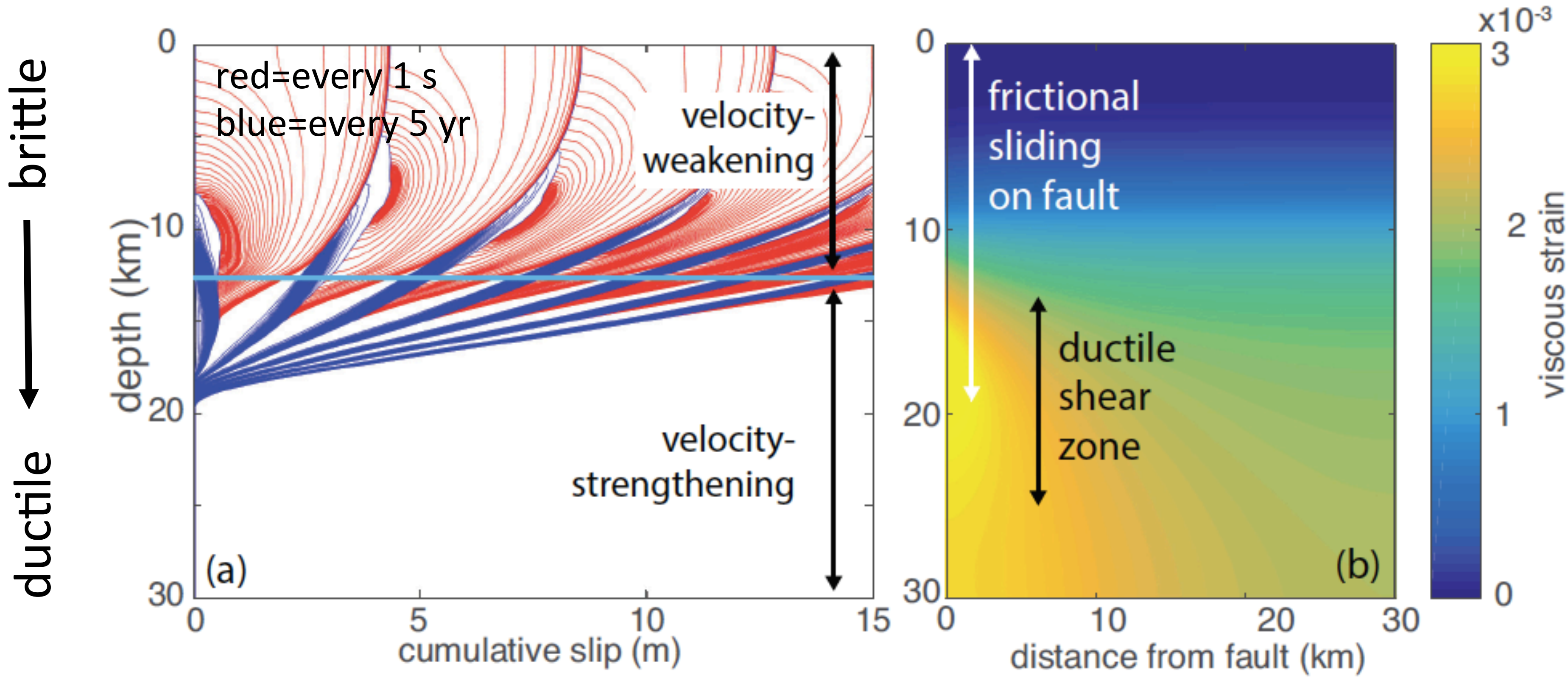
$$d\varepsilon/dt = Ae^{-Q/kT}\tau^{n}$$

(classic "crustal strength profiles")

Strength will vary over earthquake cycle with changes in strain rate and temperature (heating from viscous flow and frictional sliding).

Viscoelasticity and Earthquake Cycles

preliminary results: cycles in linear *Maxwell viscoelastic solid* with viscosity set by background geotherm (no thermomechanical coupling)

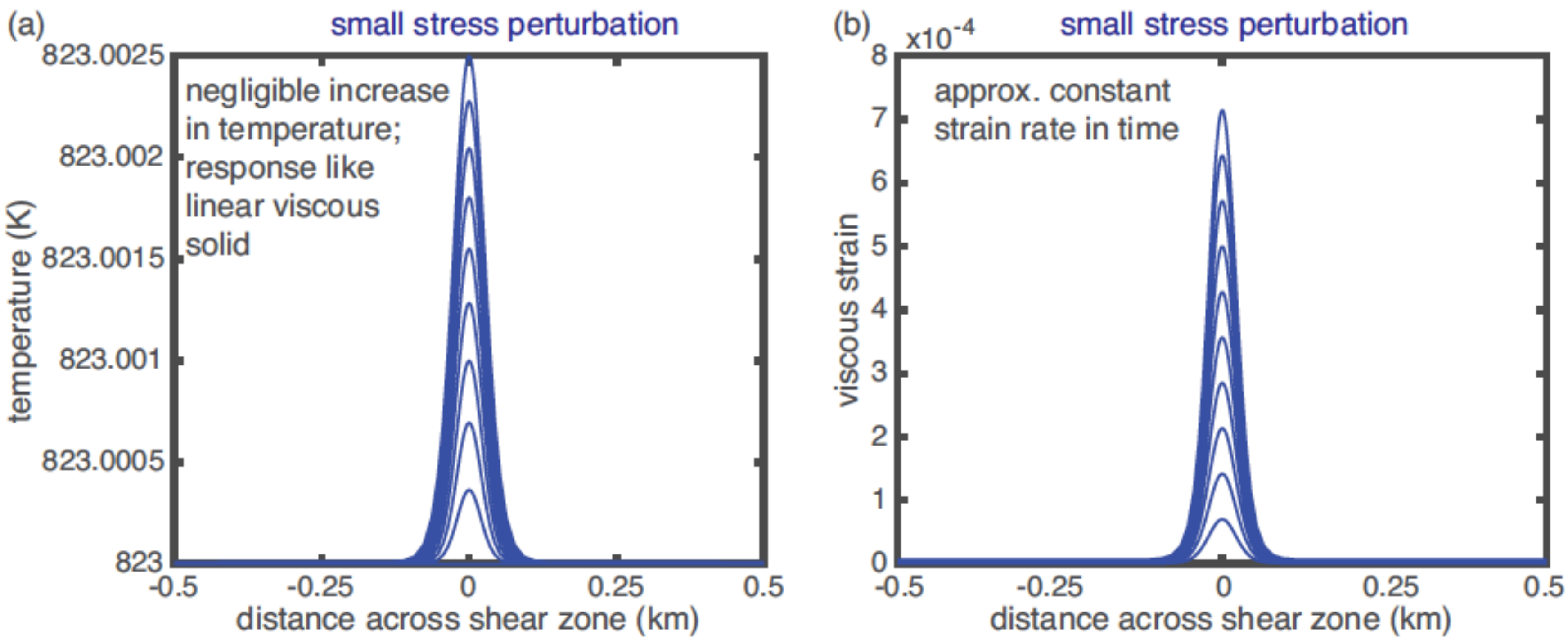


[Allison and Dunham, work in progress, 2016]

Next step is to evolve temperature by solving energy equation with heating from viscous flow and frictional sliding, accounting for temperature and strain rate dependence of rheology.

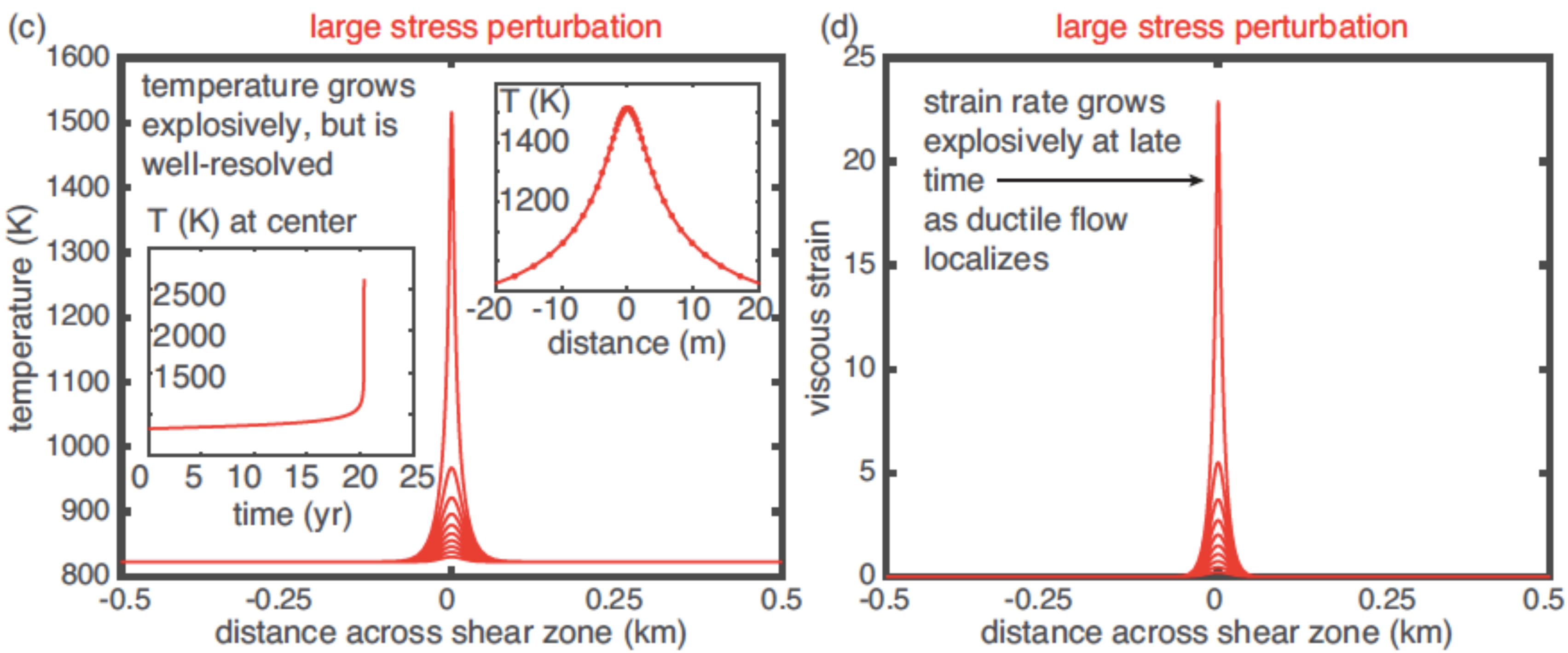
Thermomechanical Coupling and Ductile Shear Localization

How do ductile shear zones respond to earthquakes?
snapshots every 2 yr following stress perturbation from coseismic slip



Thermomechanical Coupling and Ductile Shear Localization

How do ductile shear zones respond to earthquakes?
snapshots every 2 yr following stress perturbation from coseismic slip



This example illustrates rich and complex behavior that might emerge from **thermomechanical cycle modeling**. Similar shear heating instabilities have been suggested to generate seismicity, at least at intermediate depths [e.g., Hobbs et al., 1986; Ord and Hobbs, 1989 ; Keleman and Hirth, 2007].

Conclusions and Future Work

- *dynamic rupture simulations* of single events provide useful outputs
- but we need better constraints on *initial conditions* (stress), which means incorporating much *longer time scale loading processes* commonly thought of as "***geodynamics***"
- major opportunities exist with *thermomechanical cycle modeling*, making connections to crustal deformation, mantle convection and plate tectonics, as well as anthropogenic forcing (induced s